

# A simulation code to assist designing space missions of the Airwatch type

T. Montaruli<sup>a</sup>, R. Bellotti<sup>b</sup>, F. Cafagna<sup>a</sup>, M. Circella<sup>a</sup>, C. N. De Marzo<sup>b</sup> and P. Lipari<sup>c</sup>

<sup>a</sup> Sezione INFN di Bari, Via Amendola 173, 70126 Bari, Italy

<sup>b</sup> Dip. di Fisica, Univ. di Bari and Sezione INFN di Bari, Via Amendola 173, 70126 Bari, Italy

<sup>c</sup> Sezione INFN di Roma, Univ. di Roma I, P. A. Moro, 00185 Roma, Italy

## ABSTRACT

The design of an Airwatch type space mission can greatly benefit from a flexible simulation code for establishing the values of the main parameters of the experiment. We present here a code written for this purpose. The cosmic ray primary spectrum at very high energies, the atmosphere modelling, the fluorescence yield, the photon propagation and the detector response are taken into account in order to optimize the fundamental design parameters of the experiment, namely orbit height, field of view, mirror radius, number of pixels of the focal plane, threshold of photo-detection. The optimization criterion will be to maximize counting rates versus mission cost, which imposes limits both on weight and power consumption. Preliminary results on signals with changing energy and zenith angle of incident particles are shown.

**Keywords:** Extreme energy cosmic rays, fluorescence, simulation

## 1. INTRODUCTION

In recent years, the extremely high energy region of the cosmic ray spectrum ( $10^{18} - 10^{21}$  eV) has been attracting more and more attention because of the fundamental questions (in High Energy Astrophysics) concerning the origin and propagation of detected particles of such high energy. High energy cosmic rays are detected by measuring the large showers they produce in the Earth atmosphere which acts as a giant detector for incoming extraterrestrial radiation. Extreme Energy Cosmic Ray (EECR) induced showers produce fluorescence light in the atmospheric nitrogen that can be observed by detectors like Fly's Eye.<sup>1</sup> In this way the observable quantities that can be measured in order to study the EECR are longitudinal shower profile, depth and size of the shower maximum and arrival direction. From these observables angular anisotropy, energy, nature and composition of the primary particles have to be derived.

Recently the possibility of observing the fluorescence light induced by the EECR in the atmospheric nitrogen from space platforms has been proposed,<sup>2,3,4</sup> hence providing an alternative approach to very large ground based arrays. In fact, in measuring the cosmic ray spectrum up to the highest energies severe conditions are posed by the particle flux, which at energies higher than 3 EeV appear to decrease as  $E^{-\alpha}$ , with differential spectral index  $\alpha = 2.7$ . As a consequence, observations at these energies have to cope with fluxes lower than one particle per square kilometer per millennium. Indeed detectors on space platforms appear to provide the possibility of extending the EECR measurements beyond  $10^{21}$  eV<sup>5,6</sup> due to the large atmospheric volume that can be looked at by a single detector. Anyway, the detection of the EECRs through the fluorescence light induced in the atmosphere requires detectors with good sensitivity in the UV and in the optical ranges, large collecting optics and a focal plane segmentation up to a million pixels. Such requirements are particularly compelling for an Airwatch type detector,<sup>7</sup> since in this case the showers will be reconstructed on the basis of the image detected by a single satellite with proper time information. The construction of such a detector in the present situation requires both a substantial R&D and a design optimization effort. To this aim the study of the mission configuration with a simulation code offers a cheap and flexible way to decide optimal values for parameters before starting the detector construction.

We present here the first steps we have implemented in the simulation of a mission of the Airwatch type.

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Further author information:

(Send correspondence to)

C. N. D.: E-mail: [demarzo@ba.infn.it](mailto:demarzo@ba.infn.it)

T. M.: E-mail: [montaruli@ba.infn.it](mailto:montaruli@ba.infn.it)

## 2. THE SIMULATION CODE ARCHITECTURE

The aims of the simulation code are:

- to study at a first order precision the feasibility of an Airwatch type mission and its main features, such as geometrical parameters, orbit height, energy threshold, capabilities of the photodetector;
- to estimate counting rates for given detector features.

In order to fulfil these aims many parameters are input to the algorithm and hence are easily changeable.

The flow-chart of the algorithm is:

1. geometry initialization. At this stage 3 input parameters are required: the orbit height  $H$ , half of the field of view angle  $\theta_{FOV}$ , the threshold for the detection of photons in terms of photoelectrons  $(p.e.)_{thr}$ . We have assumed that the photodetectors are capable of resolving one single p.e.;
2. initialization of the energy distribution of primaries. There are two possible choices to run the program: using a fixed value of the primary energy or an energy randomly generated from a given energy spectrum. In the former case the input to the simulation is the energy of the primary, in the latter it is the minimum energy of the spectrum  $E_{min}$ . We have assumed a pure proton component with a structure at  $E^* = 3.162$  EeV (according to Fly's Eye observations<sup>8</sup>). The differential spectral index of the flux is  $\alpha_1 = 3.27$  for energies lower than  $E^*$  and  $\alpha_2 = 2.71$  for energies higher than  $E^*$ ;
3. initialization of the shower development process: initializes hadron interaction cross sections (according to the SIBYLL model<sup>9</sup>), electromagnetic cross-sections (pair production and bremsstrahlung), the muon energy loss for ionization in air. We point out that our aim here is to investigate the experimental configuration rather than to discuss the models of shower development in the atmosphere at such high energy (above  $10^{19}eV$ ). The structure of the code is such that any parametrization of cross sections from any model can be easily implemented;
4. event generation (input: the number of events to be generated):
  - generation of the impact point of the trajectory on the Earth surface;
  - generation of the direction of the track of the primary;
  - generation of the energy of the event according to the initialization choice explained above;
  - structure of the atmosphere and conversion between slanted depth along the track and vertical height;
  - shower development \*: the charged particles developed in the atmosphere (size) are counted in the proper number of steps in which the track is divided. The secondary particles of the shower are assumed to be in the same direction of the incident particle in an unidimensional approximation;
  - *i*) fluorescence light generation; *ii*) propagation onto the light collector and focalization on the detector pixel matrix; *iii*) quantum conversion into photoelectrons;
  - record of the relevant information for each event.

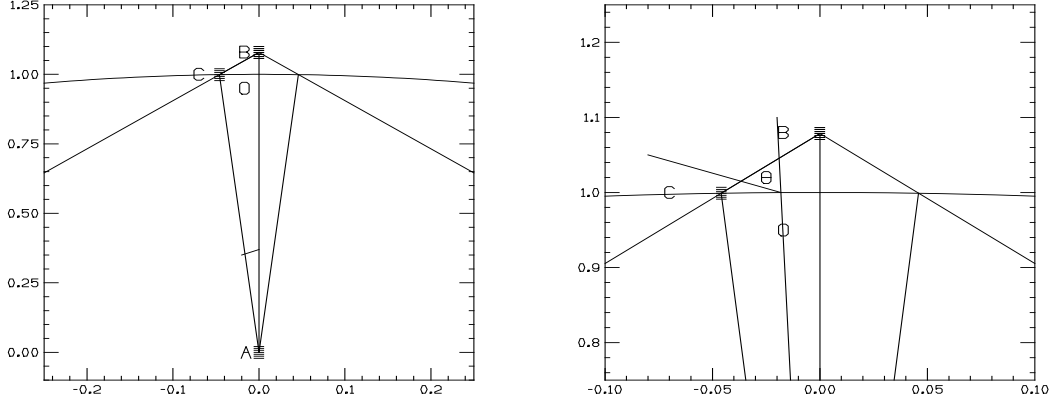
In Fig. 1 the parameters used for describing the region of the atmosphere seen by the detector are schematically shown. The orbit height  $H$  and  $\theta_{FOV}$ , together with the radius of the Earth  $R_{\oplus}$ , determine the opening angle  $\theta^*$  of the cone with the vertex in the center of the Earth which sees the same area  $A$  as seen by the detector:

$$\cos \theta^* = \frac{(1 + \frac{H}{R_{\oplus}}) \tan^2 \theta_{FOV} + \sqrt{1 + \tan^2 \theta_{FOV} - (1 + \frac{H}{R_{\oplus}})^2 \tan^2 \theta_{FOV}}}{(1 + \tan^2 \theta_{FOV})}. \quad (1)$$

Hence, considering the reasonable values  $H = 500$  km,  $\theta_{FOV} = 30^\circ$ , then  $\theta^* = 2.6^\circ$ , the area on the curved Earth surface seen by the detector is  $A = 2\pi R_{\oplus}^2 (1 - \cos \theta^*) = 2.7 \times 10^5$  km<sup>2</sup> having a radius of 289 km. Given this area,

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\*At the moment the shower is initiated only by protons; in the future the superposition principle will be applied in order to consider showers initiated by heavier nuclei.



**Figure 1.**

Schematic view of the detector (B). The orbit height is  $\overline{OB}$ , the radius of the Earth is  $\overline{AO}$ , the angle  $\theta^*$  is  $\widehat{OAC}$  and the angle  $\theta_{FOV}$  is  $\widehat{OBC}$ . The plot on the right is an expanded view of the one on the left where an example of generated zenith angle  $\theta$  is shown.

the acceptance is approximately  $Acc = 2\pi A$  (because the Earth blocks cosmic rays for half of the sky) and hence the expected rate for the integral flux considered (from Fly's Eye data) is for  $E_{min} = 10^2$  EeV, without considering any efficiency:

$$Rate = Acc(km^2 sr) \times Flux(E \geq E_{min})(km^{-2} yr^{-1} sr^{-1}) = 1.5 \times 10^4 events/year. \quad (2)$$

The geometrical parameters relevant for the detector are the area of the mirror which collects the fluorescence photons, assumed  $5 \text{ m}^2$ , and the structure of the pixel matrix. The order of magnitude of the number of pixels needed depends on  $\theta_{FOV}$ , on  $H$ , on the length of tracks  $\ell$  in the atmosphere and on the number of sampling points along the track  $N$ . For typical values of  $\ell = 10 \text{ km}$  and  $N = 30$ :<sup>5</sup>

$$N. \text{ of pixels} = \sin^2 \theta_{FOV} N^2 \left( \frac{2H}{\ell} \right) \sim 10^6. \quad (3)$$

In order to understand the geometry of the problem one has to consider the relation between the reference system of the detector (which we call *global*) and the *local* reference system with the origin in the center of the Earth and the  $z$  axis passing through the detector ( $z = \overline{AB}$ ). The criteria to generate each event is to randomly choose an angle  $\theta_p$  between  $\theta^*$  and 0 and  $\varphi_p$  between 0 and  $2\pi$ . This means to extract a point  $P$  on the Earth surface inside the area  $A$ . The coordinates of this point in the local reference system are  $(R_\oplus \sin \theta_p \cos \varphi_p, R_\oplus \sin \theta_p \sin \varphi_p, R_\oplus \cos \theta_p)$ . Then the direction of the shower is generated randomly (the zenith angle  $\theta$  and the azimuth  $\varphi$ ) with respect to a reference system with the origin in the point  $P$  and the  $z$  axis at the vertical of the Earth surface. Being  $Y$  the slant distance from the origin  $P$  to the first interaction point in the atmosphere  $X_0$  (which is generated at the top of the atmosphere considering the interaction length of protons) the coordinates of any point  $P(Y)$  along the track in this reference system are  $(Y \sin \theta \cos \varphi, Y \sin \theta \sin \varphi, Y \cos \theta)$ . It is straightforward to rotate this reference system into the global one which has the origin in the detector (B) and the  $z$  axis toward the center of the Earth along the vertical of the Earth ( $\overline{BA}$ ). The coordinates of the point  $P(Y)$  in this system are  $(x(Y), y(Y), z(Y))$  and the plane  $xy$  is the pixel matrix plane. The angular coordinates of the point  $P(Y)$  on the pixel matrix are  $(\sin \theta_m \cos \varphi_m, \sin \theta_m \sin \varphi_m) = (x/D, y/D)$ , where  $D = \sqrt{x^2 + y^2 + z^2}$  is the distance of  $P(Y)$  from the detector.

Assuming a total number of pixels of  $N_0 = 10^6$ , located on a circular matrix, they can be defined as squares and labelled between  $-N_A$  and  $N_A$  where  $N_A = \sqrt{\frac{N_0}{\pi}}$  ( $\pi N_A^2 = N_0$ ) along x and y. Hence, their constant angular width is  $dx = dy = \sin \theta_{FOV}/N_A$ . The number of pixels which effectively view tracks (i.e. satisfy  $A_{ij} = \sqrt{(x_i/D)^2 + (y_j/D)^2} < \sin \theta_{FOV}$ ) is 999289 in this arrangement and the total solid angle seen by the pixels is  $d\Omega = \sum_{ij} \frac{dx dy}{\sqrt{1-A_{ij}^2}} = 0.84$  sr.

In Tab. 1 the main parameters of the mission and the transmission and detection efficiencies<sup>5</sup> are summarized. The product of all the efficiency terms gives a reduction factor of the signal of  $\varepsilon = 0.053$ .

**Table 1.** Main characteristics of the simulated detector: half of the field of view angle, orbit height, number of pixels, area of the mirror, optical efficiency of the mirror, atmospheric Rayleigh transmission, ozone transmission and quantum efficiency of the photodetector.

$\theta_{FOV}$	$H$	N. of pixels	area of mirror	optical effc.	UV filter effc.	atmosph. Rayleigh transm.	atmosph. ozone transm.	Q.E.
30°	500 km	10 <sup>6</sup>	5 m <sup>2</sup>	0.85	0.6	0.568	0.736	0.25

Once a primary particle has been generated with its incident energy and its zenith and azimuth angles, the relation between the slant distance along the track  $Y$  (km) ( $Y = 0$  on the Earth surface) and the vertical height  $Z$  along the vertical of the Earth ( $Z$  is 0 at the detector level and  $Z$  is maximum at the Earth surface) is:

$$Z = \sqrt{R_{\oplus}^2 + Y^2 + 2R_{\oplus}Y \cos \theta} - R_{\oplus}. \quad (4)$$

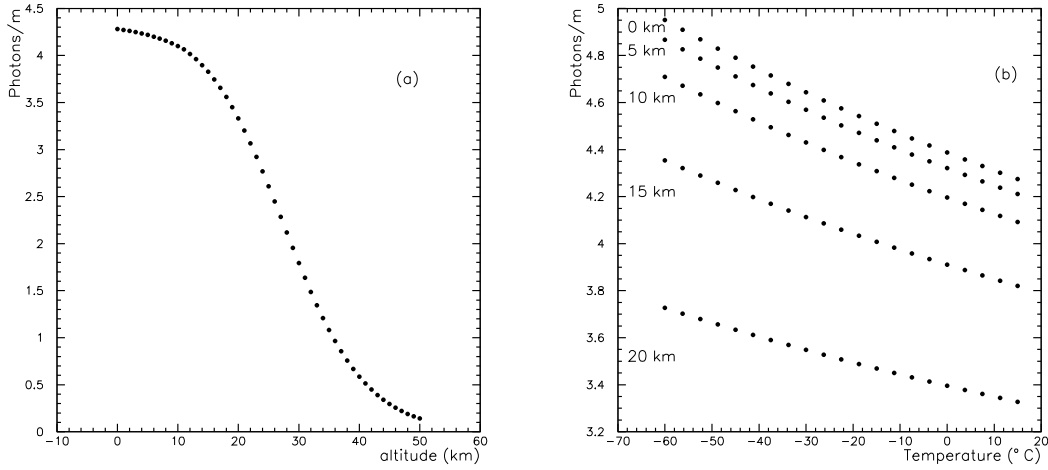
The slant distance is connected to the slant depth  $X$  (gr/cm<sup>2</sup>) along the track considering the density of the atmosphere, which varies with height. The track slant depth is divided into 30 equispaced pieces, whose size is then calculated using a shower development code. The shower cascade algorithm is based on a routine named UNICAS<sup>10</sup> which generates a shower due to the interaction of a single nucleon starting at a slant depth  $X_0$  and interactions and decays of particles are treated. The hadronic interactions are treated according to the splitting algorithm by Hillas (described in<sup>10</sup>) with threshold energies (down to which particles are tracked)  $\sim 89 \times 10^3$  TeV. Cross sections for hadron interactions are obtained from the SIBYLL model.<sup>9</sup> The SIBYLL model is based on the idea that the increase in cross section is driven by the production of minijets<sup>11</sup> with particular emphasis on the fragmentation region (appropriate for cosmic rays) and on collisions of hadrons with light nuclei. The ideas of the dual parton model<sup>12</sup> are incorporated. The code is tailored and efficient at energies up to at least  $10^{20}$  eV. The main outcomes of the code are the depth and size of shower maximum.

Once the number of charged particles for each step and the shower maximum and size at maximum have been determined, a track of photons is produced on the detector focal plane. The photoelectron number per pixel obtained for each step is extracted from a poissonian distribution of mean value:

$$(N_{p.e./pixel})_i = \frac{A_{mirror}}{4\pi R^2} \varepsilon_{light} S \varepsilon, \quad (5)$$

where  $i$  labels the piece of track,  $A_{mirror}$  is the area of the collecting mirror,  $R$  is the distance of the piece from the detector,  $\varepsilon_{light}$  is the number of photons produced per particle per unit length,  $S$  is the size of each piece and  $\varepsilon$  is the efficiency factor which includes all terms in Tab. 1. In Fig. 2 the behaviour of  $\varepsilon_{light}$  as a function of the altitude and of the temperature is shown.<sup>13</sup> The fluorescent yield at STP in the range 300-400 nm is 4.27 photon/meter/particle.

The most interesting information on simulated events are stored, namely the energy and the zenith angle of the incoming particle, the number of photoelectrons per pixel on the detector, the number of photoelectrons in pixels which detect a signal (above the detection threshold of 1 p.e.), the total number of pixels hit and those above threshold, the size and the slant depth of the maximum of the shower.



**Figure 2.**

(a) Fluorescent yield of photons/particle/meter in the range 300-400 nm as a function of the altitude at STP. (b) Fluorescent yield ( $\gamma/\text{particle}/m$ ) as a function of temperature for 5 different altitudes.<sup>13</sup>

In Fig. 3 we show two simulated “photon tracks” on the pixel matrix for two values of the energy of the primary particles differing by 1 order of magnitude and impinging with the same zenith angle.

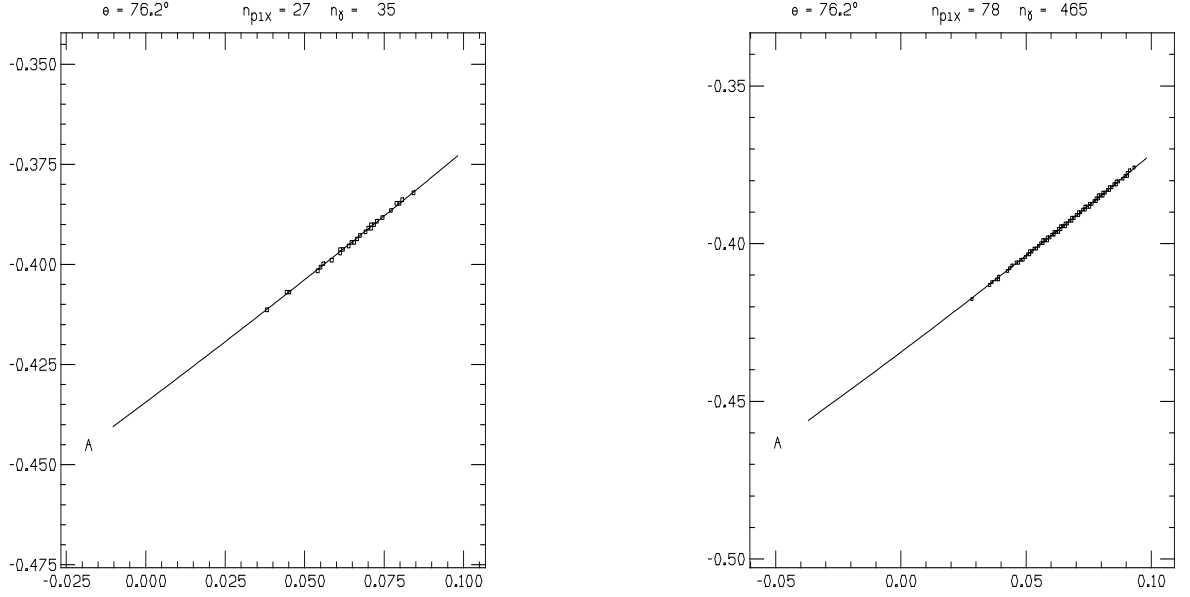
In Fig. 4 the total number of pixels above threshold versus the total number of photoelectrons is shown for all events for minimum energies of the primary spectrum  $E_{min} = 10$  and 100 EeV. In Fig. 5 the distribution of the number of pixel hit above threshold for all the events is shown. The mean value of the number of detected photons is increased by a factor of 2 when the minimum energy is increased from 10 EeV to 100 EeV.

In Fig. 6 the number of pixels hit above threshold summing over all events is shown for two values of the minimum energy considered (10 and  $10^2$  EeV) versus the cosine of the zenith angle of the track in the local system. These plots are very important in establishing two facts:

1. even if vertical tracks are more abundant than horizontal ones, it is clear that the detection of almost horizontal tracks is favoured by the large number of pixels hit. This is important in view of the detection of neutrinos as horizontal showers crossing huge amounts of atmosphere;
2. the energy threshold of the detector is a critical parameter: the aim of the mission is to investigate the region of the ankle of the cosmic ray spectra, but the possibility of measuring showers with energy as low as  $10^{18}$ - $10^{19}$  eV could provide interesting hints for what concerns neutrino physics items such as investigations on active galactic nuclei and neutrino astronomy. Moreover the lower the threshold the higher the statistics that can be achieved due to the power law behaviour of the cosmic ray spectrum. Another important aspect of having a low threshold is that the space mission data could be compared to the ground based ones, hence providing a calibration opportunity for this new kind of detector with respect to a more traditional technique. The plot in Fig. 6 (a) shows that the detection at  $10^{19}$  eV is feasible.

### 3. CONCLUSIONS

At the current stage of investigation presented in this work the simulation code is already an useful tool for designing Airwatch type missions. As a further step, the timing of each photon reaching the focal plane will be implemented. This will give the development in time of the detector electronic signals. This knowledge is fundamental in order to derive the shower axis direction in the Airwatch concept. This will allow an estimation of the background level, which depends on the integration time of the acquisition system.



**Figure 3.**

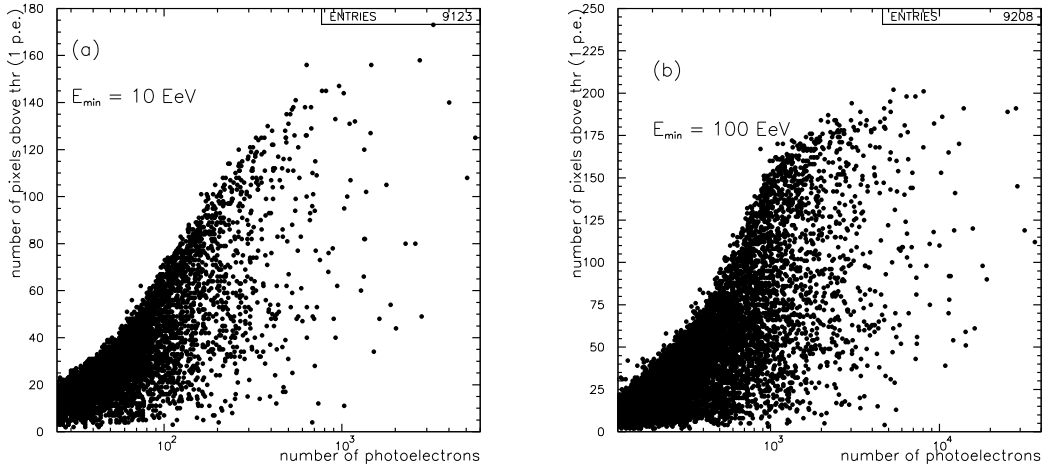
Schematic plots of events as seen on the pixel matrix (the plane  $(\sin \theta_m \cos \varphi_m, \sin \theta_m \sin \varphi_m)$ ): the event on the left (right) has been generated by a primary particle of energy 11 EeV (111 EeV). The zenith angle of the primary is in both cases  $76.2^\circ$ . The letter A stands for the first interaction point. The shown track represents the projection of the atmospheric track onto the matrix plane. The squares are the pixels with at least 1 p.e.. There are 27 (78) pixels hit for a total number of 35 (465) photoelectrons for the event on the left (right).

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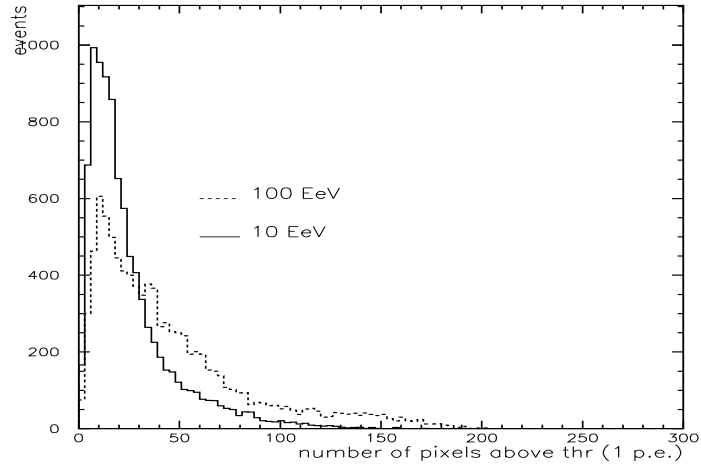
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**Figure 4.**

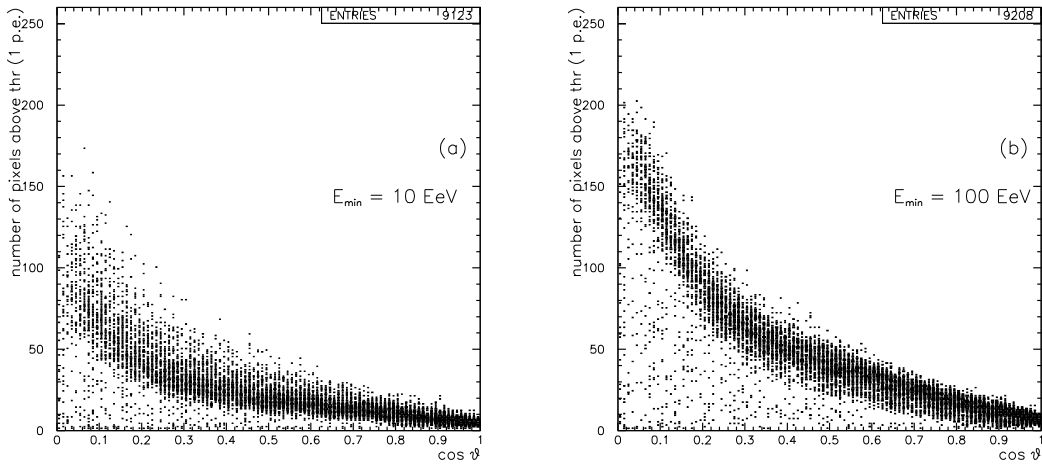
Number of pixels hit above threshold (at least 1 p.e.) vs number of photoelectrons (a) for incident primaries with energy above 10 EeV; (b) above 10<sup>2</sup> EeV. 10000 events were generated for each plot. Those which produce at least 1 p.e. on the pixels are 9123 in the case of 10 EeV and 9208 in the case of 100 EeV. In order to match the size of pixels, the number of steps in which the track is divided in the atmosphere (30) is increased to 300 (maximum number of pixels hit in one event) when projecting the track onto the pixel matrix.

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**Figure 5.**

Distribution of the number of pixels hit above threshold (at least 1 p.e.) for incident primaries with energy above 10 EeV and above  $10^2$  EeV.



**Figure 6.**

(a) Number of pixels which measure at least one p.e. as a function of the cosine of the zenith angle of the incident primaries with energy above 10 EeV. (b) Same as (a) but for minimum energy  $10^2$  EeV. The two plots have been obtained generating  $10^4$  events.